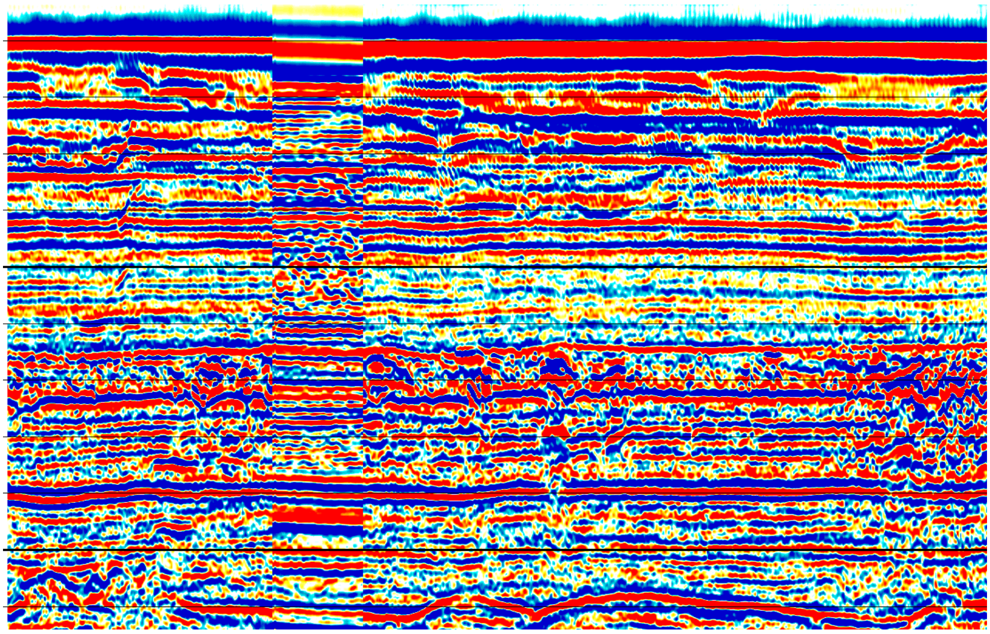
AUSTRALIAN PETROLEUM COOPERATIVE RESEARCH CENTRE

Curtin UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF EXPLORATION GEOPHYSICS

GEODISC Project 6
Monitoring CO_2 Injection



Experimental Project on Physical Modelling of the Geophysical Response of Carbon Dioxide Injection – Phase 1: Modelling the Sleipner West Overburden

A report to the APCRC GEODISC Program

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1. Background

Sleipner West is located in the Norwegian sector of the North Sea and is the site of the world's first commercial-scale CO_2 storage project. The project has been operating for over 3 years with in excess of 2 million tonnes of CO_2 now stored underground. To monitor the storage of the sequestered CO_2 a project called the Saline Aquifer Carbon Dioxide Storage (SACS) project was established. In the first collaborative experimental project, the Australian GEODISC program will collaborate with SACS to build a physical model of Sleipner West. The model will be used to study the geophysical response of CO_2 injected into the Utsira Formation. The model will assist in developing an understanding of the movement of the injected CO_2 within the Utsira formation. Establishing how the injected CO_2 will remain in the Utsira formation after injection and identifying its possible migration paths is critical to the estimation of how long the CO_2 will be stored in the reservoir. For underground storage of CO_2 in geological formations to be accepted as a mitigation option it will be necessary to demonstrate that long-term storage is feasible.

The use of physical models is well established as a method to simulate and thereby understand the reflected 3-D seismic wavefield characteristics of a particular form of geological structure. The advantages of physical models are that the ultrasonic sources and receivers are always the same, the computer controlled navigation is identical, the processing algorithms are consistent and complications from seasonal or climate changes are absent (McKenna, et al., 2000). This means that the physical modelling laboratory provides the ideal environment to study the time variant aspects of fluid flow within porous media (Sherlock et al., 2001). Most of the problems that plague field studies can be by-passed so that any anomalies observed on difference sections can be directly attributed to changes that have occurred within the model.

2. Project Outline

The experimental monitoring study of CO_2 flow within a physical model simulating Sleipner West has been divided into two phases. The objective of Phase 1 (the focus of this report), was to construct a 1:5000 scale model representative of the sedimentary sequence overlying the CO_2 reservoir (Utsira Formation) consisting of five horizontal layers. Using the physical modelling system at Curtin University of Technology, scaled seismic data was acquired over the model and processed to match the field seismic data of the 1994 base survey. Phase 2 of this experimental project will then incorporate a synthetic sandstone reservoir into the model and CO_2 (or equivalent fluid) injection performed. The controlled laboratory environment will provide improved understanding of the seismic response to CO_2 sequestered in the Utsira sand.

3. Sleipner West Geology

The Utsira sand is directly overlain by sediments of the Nordland Group (Isaksen and Tonstad, 1989; Eidvin et al., 1999), which are predominantly shale in the lower section although a thin sand wedge unit is present across most of the Sleipner area (Fig. 1). These sediments will provide the seal for the CO_2 sequestered within the Utsira formation. The Pliocene shales can be subdivided into two units. The Lower Pliocene has a shale drape at its base that can be distinguished on regional scale and exhibits locally anomalously high seismic amplitudes. The Upper Pliocene prograding unit is characterized by irregular internal reflectors and frequently occurring very high amplitudes. The amplitude anomalies in these units might be due to isolated high-velocity lithologies, or alternatively to the presence of shallow gas (Gregersen et al., 2000; Arts et al., 2000). Overlying the Nordland Shales are the Quaternary Sands, which exhibit a seismic expression representative of numerous horizontal layers.

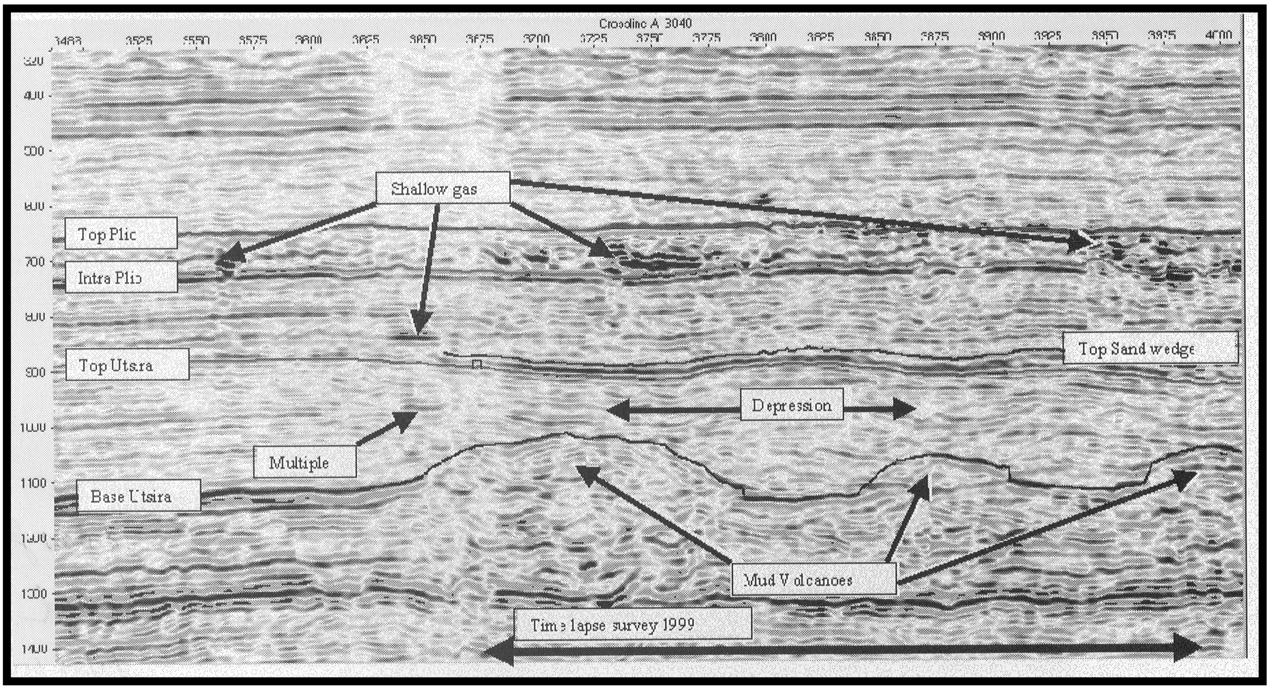

Figure 1 – The Nordland Shales and the Quaternary Sand units overlie The Utsira sand. The Nordland shales exhibit anomalously high reflection amplitudes that may be attributed to isolated high-velocity lithologies or the presence of shallow gas (after Arts et al., 2000).

4. Physical Modelling

The history of seismic physical modelling began in the early 1920s but restrictions were imposed on the recording of reflection data in the presence of high amplitude surface wave energy because of the limited dynamic range of early recording systems. The advent of computer technology and advances in ultrasonic technology has since resolved these data acquisition problems. Because of its size, repeatability and control, seismic physical modelling offers an inexpensive, rapid and accurate form of seismic information. For this reason, seismic physical modelling has broad application, ranging from an understanding of fundamental wave propagation (O'Brien, 1955; Donato, 1960 (a,b); Levin and Robinson, 1968), to improved imaging of complex subsurface geological structures (Ass'ad et al., 1992; Ebrom and Sheriff, 1992; Evans et al., 1995).

The physical modelling system at Curtin University uses a personal computer (PC) to drive an ultrasonic pulser unit, which sends a voltage waveform through the ultrasonic piezoelectric transducers used to simulate the seismic source and receiver (McKenna, et al., 2000). The output from a single receiver is fed into a 12-bit analog-to-digital converter and stored to the hard-drive of the PC (Fig. 4.1). Movement of the transducers is controlled in three-dimensions by stepper motors that are also driven by the PC in an x, y, and z coordinate system using a DOS program called the Seismic Acquisition Manager (SAM).

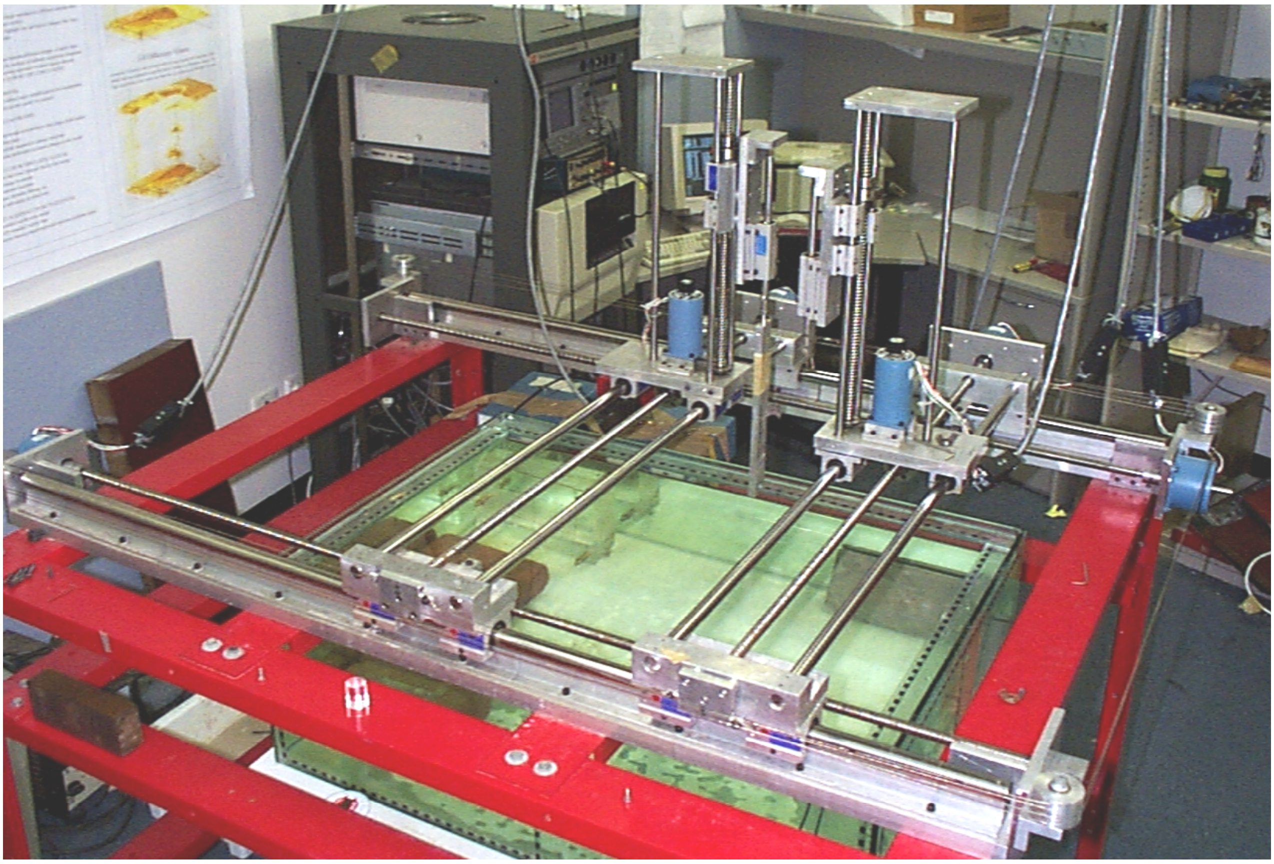

Figure 4.1 – Seismic physical modelling system at Curtin University of Technology, Perth, Australia. A PC controls the movement of simulated seismic sources and receivers within an *x, y, z* coordinate system. The signal output from the receiver is fed into a 12-bit A/D converter, which is stored to the hard disk of the PC and downloaded over the network to seismic workstations.

5. Model Design and Construction

Phase 1 of the Sleipner Modelling project involved the construction of a solid model representative of the 5 sedimentary layers overlying the Utsira Formation. The model was built to represent field dimensions of 6 km by 4 km by 730 m (depth). The thickness, interval velocity and density for each layer were supplied by the SACS consortium and are shown in Table 5.1. When designing scaled models, it is important that geometric similarity is followed. Geometric similarity is the similarity of shape and requires that the ratio of any length within the model is equal to the same ratio in the field. This ratio is referred to as the 'scale factor' and the most significant ratio of lengths concerning seismic physical modelling is the ratio between seismic wavelength and geological feature size. For this particular case study a scale factor of 1:5000 was selected to keep the size of the model manageable whilst maintaining the desired seismic resolution. The final model dimensions were 1200 mm by 800 mm by 146 mm (Fig. 5.1).

Geological Unit	P- Velocity (m/s)	Density (g/cc)	Field Thickness (m)	Model Thickness (mm)
Quaternary	1785	2.05	480	96
Upper Pliocene	2208	2.19	95	19
Lower Pliocene	2077	2.06	135	27
Sand Wedge	2056	2.05	15	3
Lower Pliocene	2285	2.13	5	1
Utsira	2056	2.05	-	-

Table 5.1 – The relevant field specifications of the sedimentary layers overlying the Utsira formation at Sleipner West supplied by the SACS consortium. Scaled dimensions are also shown.

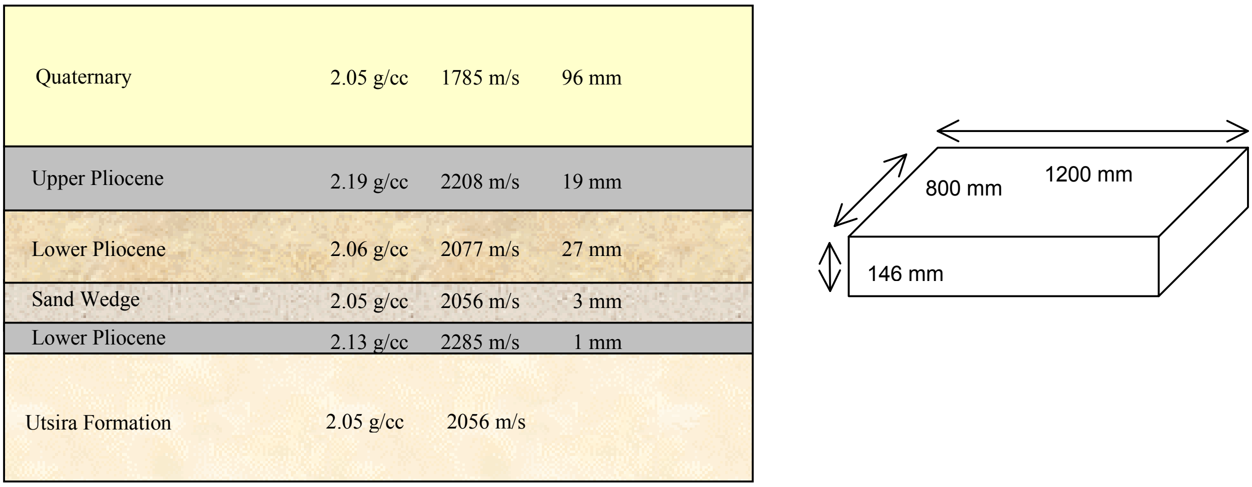

Figure 5.1 – Dimensions, P-wave velocity and density values for each layer comprising the Sleipner West overburden model.

To correctly simulate acoustic wave propagation, physical models must be constructed to match the elastic properties of the Earth. Seismic velocity and density are the most important physical properties when matching travel-times and reflection amplitudes. However, attenuation of acoustic energy is particularly high at ultrasonic frequencies and can ultimately determine the viability of materials used in model creation. Other factors to consider are cost of materials and occupational health and safety requirements. For this reason, numerous plastic and resin compounds were tested for P-wave velocity, density and attenuation to give the best match comparing field data to model travel-times, reflection amplitudes and signal strength. The material that best suited these requirements was a plastic compound comprising of two components mixed in equal parts with a limestone powder filler added to boost the P-wave velocity to match the interval velocity for each layer in the model (Fig. 5.2). Unfortunately, density values could only be matched to approximately 70% of the required values.

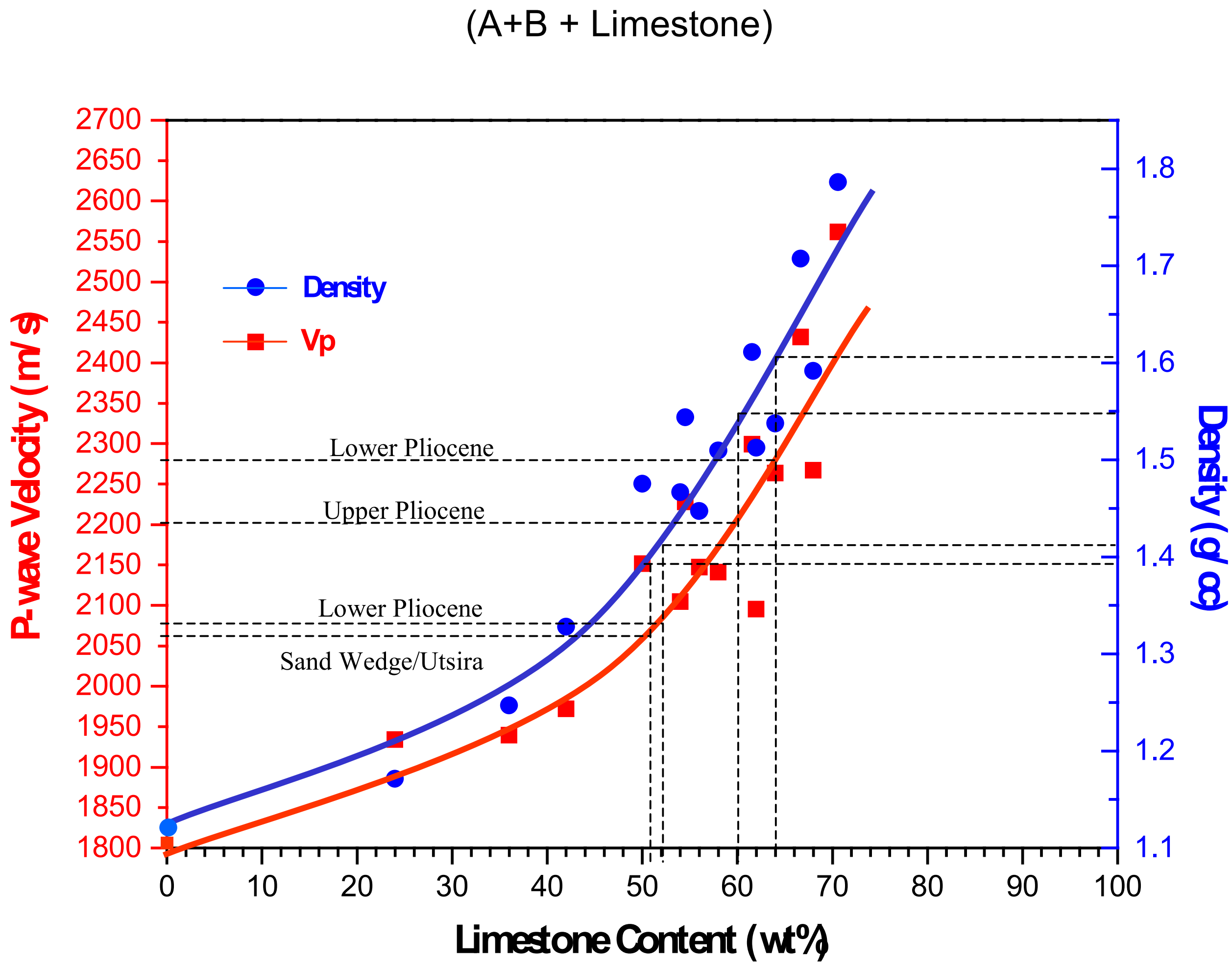

Figure 4.2 – Measured P-wave velocity and density values for each layer within the Sleipner overburden model. Parts A+B were mixed in equal amounts with limestone powder added to boost P-wave velocity and density (expressed as wt% of total mix). To match the Quaternary interval velocity, no limestone powder was added.

To create each successive layer in the model an aluminium framework was constructed around the model with internal dimensions equal to the dimensions of the layer being formed. The plastic and limestone were then mixed in a 30 litre container using an electric mixer. Once all three parts were thoroughly mixed the contents were poured into the mould and screeded level at the top using the surrounding formwork to give a flat surface. The model was then left for a period of 24 hours to allow the plastic to set before being machined and sanded to give a smooth finish (Fig 5.3). Once all five layers had been constructed (Fig. 5.4), the model weighed in excess of 250 kg. The model was then placed in a steel tank filled with water to simulate marine seismic recording. When placed into the steel tank, the model was put on legs so that there was a thin layer of water between the base of the model and the base of the steel water tank. The purpose of this thin water layer was to give a reflection from the base of the model which was more typical of the Top Utsira reflection event since no synthetic reservoir had been incorporated in the model. A synthetic Base Utsira reflection was recorded from the base of the steel tank simulated by the water-steel interface.

Figure 5.3 – After each layer in the Sleipner overburden model was formed, the layer was machined and sanded to give an even surface.

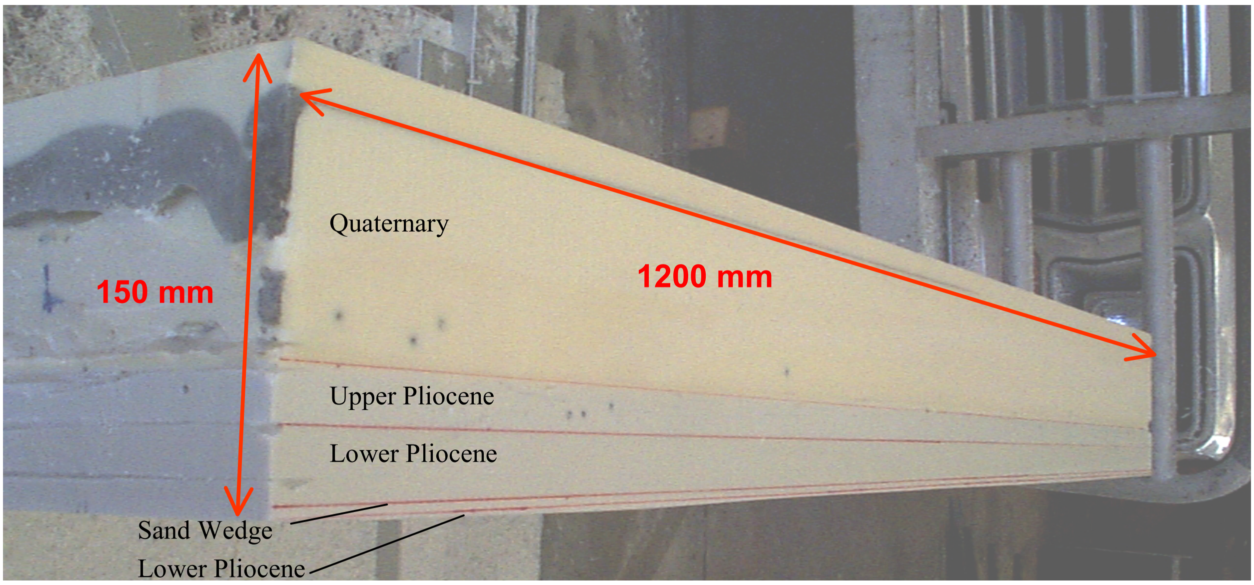

Figure 5.4 – The final Sleipner overburden model measured 1200 mm x 800 mm x 150 mm and weighed in excess of 250 kg. The model was placed in a steel tank filled with water to simulate marine seismic recording.

6. Data Acquisition and Processing

6.1 Field Data

The base seismic survey for the Sleipner CO_2 monitoring project was shot in 1994 and was acquired primarily for imaging the much deeper hydrocarbon gas reservoir (Eiken et al., 2000). The field acquisition parameters were as follows:

Shooting direction:	N-S
Energy source:	Sodera G-guns
Airgun volume:	3400 cubic inches
Shot point interval (flip flop):	18.75 metres
Gun depth:	6 metres
Gun separation:	50 metres
Number of cables:	5
Number of groups:	240
Near Offset:	250 metres
Far Offset:	3250 metres
Group interval:	12.5 metres
Cable depth:	8 metres
Cable separation:	100 metres
Inline separation:	12.5 metres
Crossline separation:	12.5 metres

The field data supplied for this project by the SACS consortium had also undergone the following processing sequence:

SEGD read and data editing
Navigation merge
Gun and cable filter delay correction (+9.46 ms)
Zero phasing
Lowcut filter (6 Hz)
Gain correction (t2)
Tidal correction
Swell noise and interference attenuation
Forward Tau-p multiple removal
Normal moveout correction
K-filter spatial resampling
Trace decimation (every second trace)

6.2 Model Data

Because the physical modelling system at Curtin comprises of only a single receiving channel, CMP data acquisition is as efficient as shot domain recording. A number of 2-D seismic lines were acquired over the model with CMP intervals of 12.5 m (scaled). Each CMP gather consisted of 100 traces with a scaled offset range from 300 m to 2300 m. 250 kHz source and receiver transducers were used in data acquisition to provide a scaled central frequency of 50 Hz. Upon SEGY import, the model data was frequency filtered, true amplitude gain (time raised to power of 2) corrected, NMO corrected and had a static shift applied before final CMP stacking. Minor problems within the model data due to a non-zero phase wavelet and multiple energy were considered insignificant and neglected during processing.

A typical raw CMP gather with automatic gain correction (AGC) applied for display purposes is shown in Figure 7.1. The gather displays the primary reflection events within the model as well other typical seismic events such as a direct wave, multiples and a coherent noise event related to the source. Internal reflection events appear within some of the sequences as a result of thicker layers being formed from multiple pourings. An example of such an event is the reflection appearing 80 ms below the water bottom reflection in Figure 7.1. The water depth for the model seismic survey was approximately 650 metres (scaled) to avoid problems with the direct wave interferring with the water bottom reflection at all offsets within the gather.

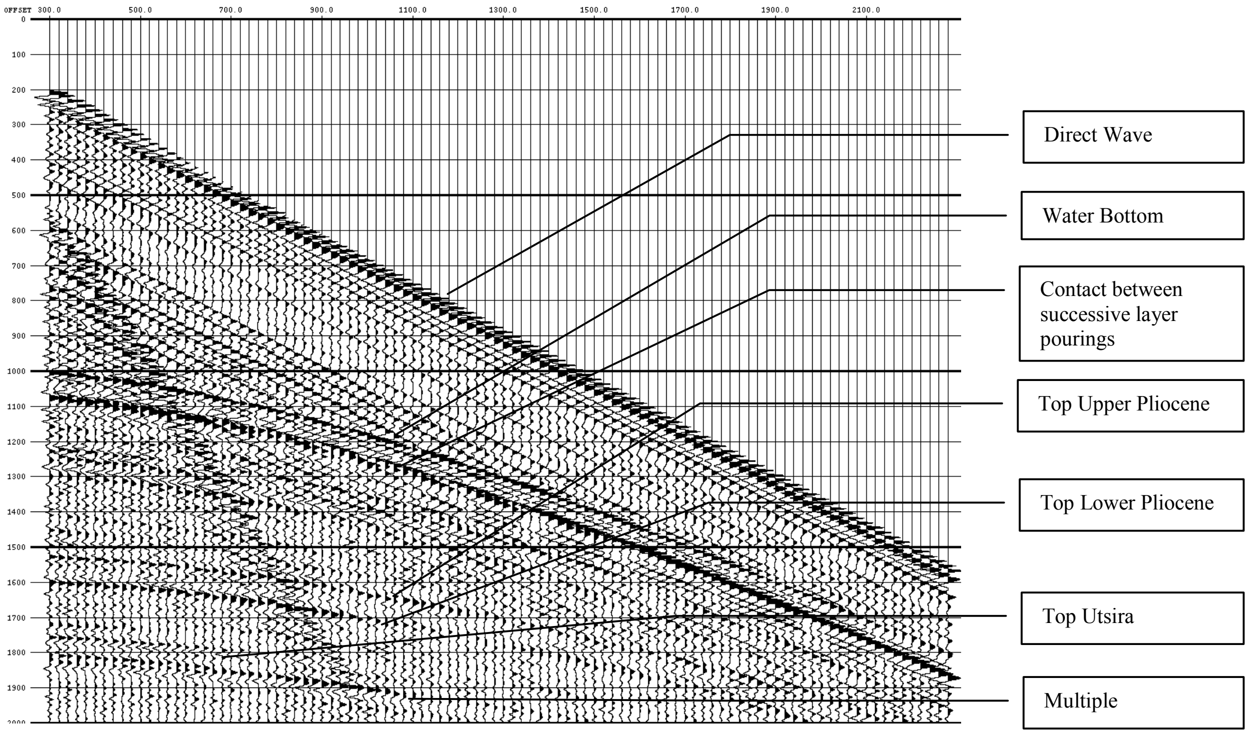

Figure 7.1 – An example of a typical raw model CMP gather with AGC applied. Reflection events were recorded from each interface within the model as well as other events such as the direct wave, multiples and an apparent coherent noise event associated with the source.

7. Model and Field Data Comparison

A single model CMP gather was compared with a typical field CMP gather (located approximately 500 metres north east of the CO_2 injection point), before NMO correction (Fig. 7.2). For comparison purposes, the model CMP gather was muted and a static shift applied to remove the effect of deeper water. Besides some minor timing differences between the primary events, the general appearance of the two gathers is very similar. The model CMP gathers were then NMO corrected and again compared with the NMO corrected field CMP gathers (Fig. 7.3). After NMO correction the model CMP gathers were stacked (Fig. 7.4) and again compared with 2-D seismic data extracted from the 1994 seismic volume (Fig. 7.5). For a closer inspection of the post-stack data matching, 60 traces from the model were inserted directly into the field data (Fig. 7.6-7.8). Overall, a successful match appears to have been achieved.

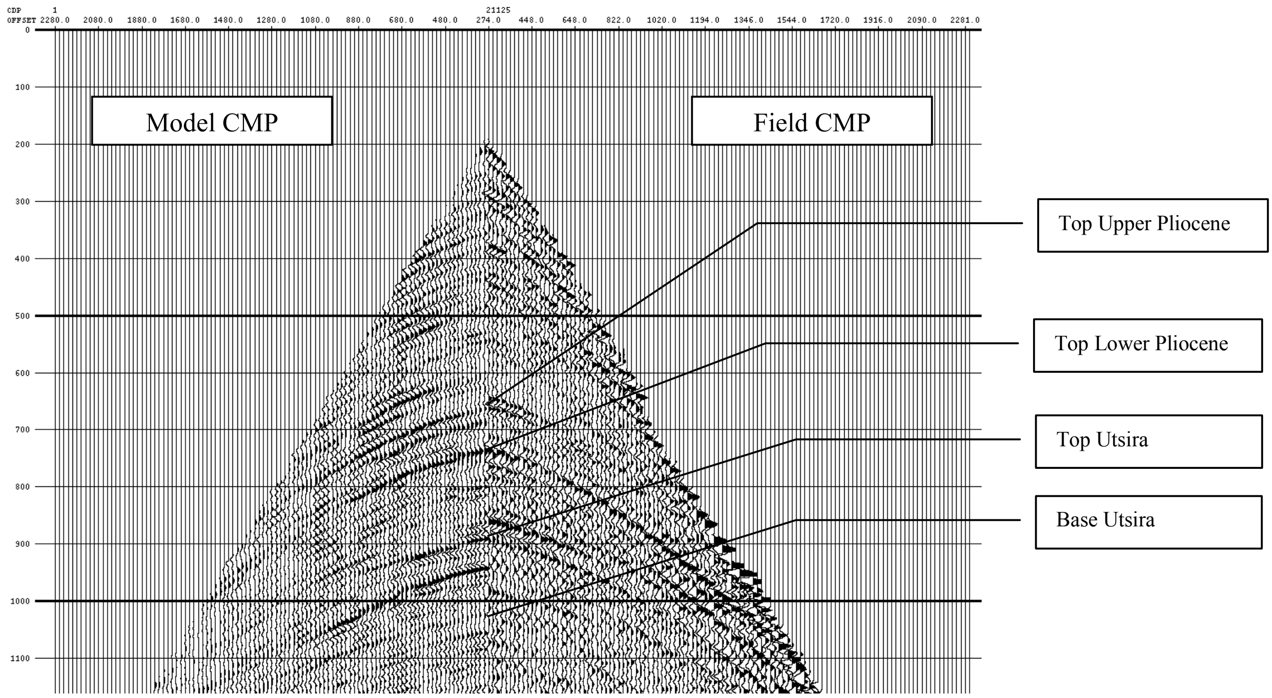

Figure 7.2 – The raw model CMP gathers were frequency filtered, true amplitude gain corrected, muted and then compared with the field CMP gathers from the 1994 survey. A typical model CMP gather is shown alongside a field CMP taken approximately 500 m NE of the CO_2 injection point.

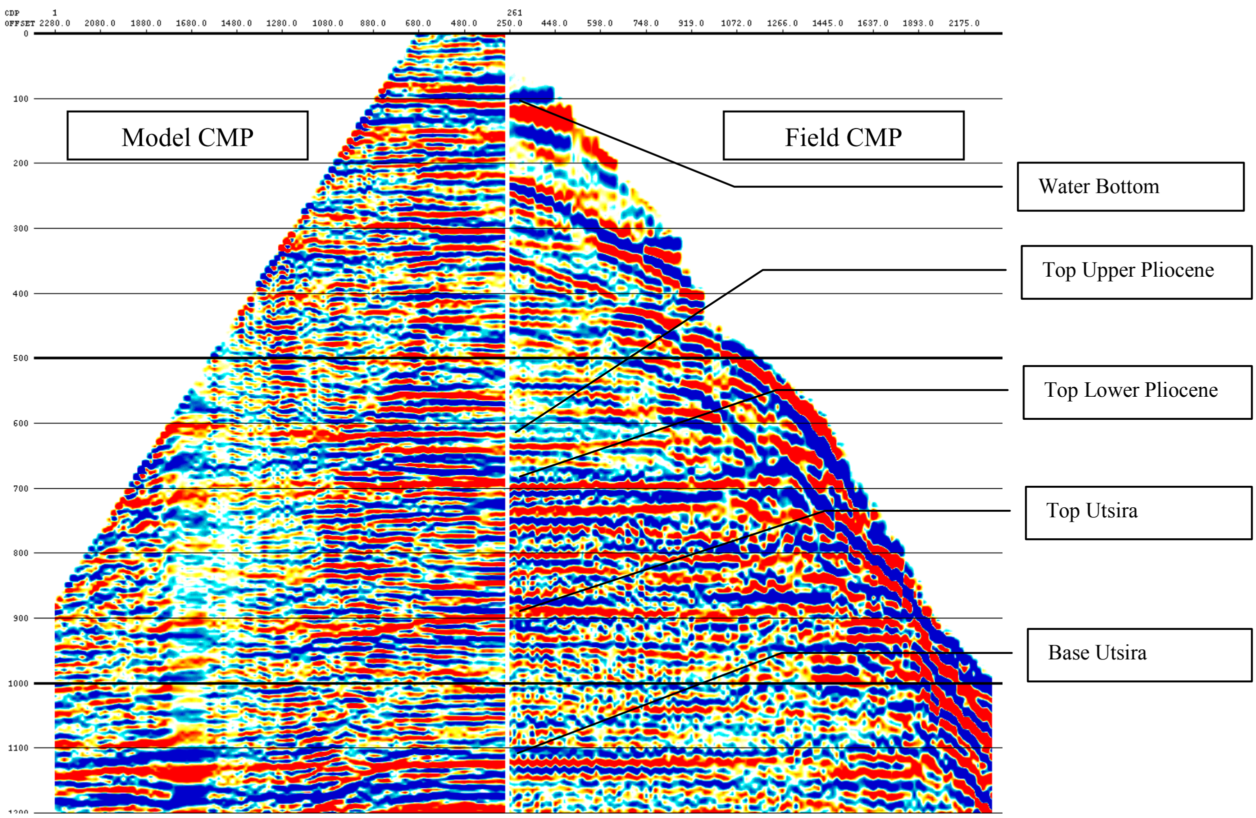

Figure 7.3 – Comparison between NMO corrected CMP gathers taken from both the model and 1994 field data.

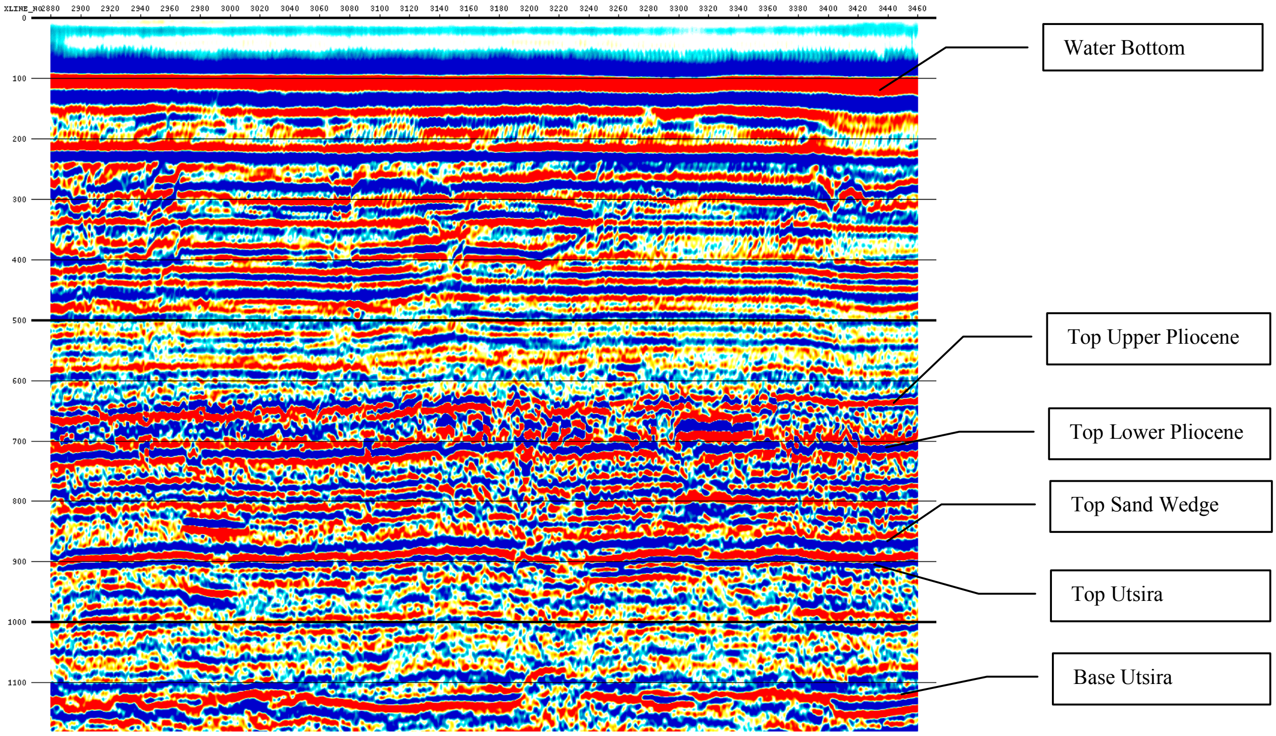

Figure 7.4 – Inline 3842 of the 1994 field seismic survey. The horizons incorporated into the Sleipner overburden model are the Top Pliocene, Top Lower Pliocene, Top Sand Wedge and Top Utsira horizons.

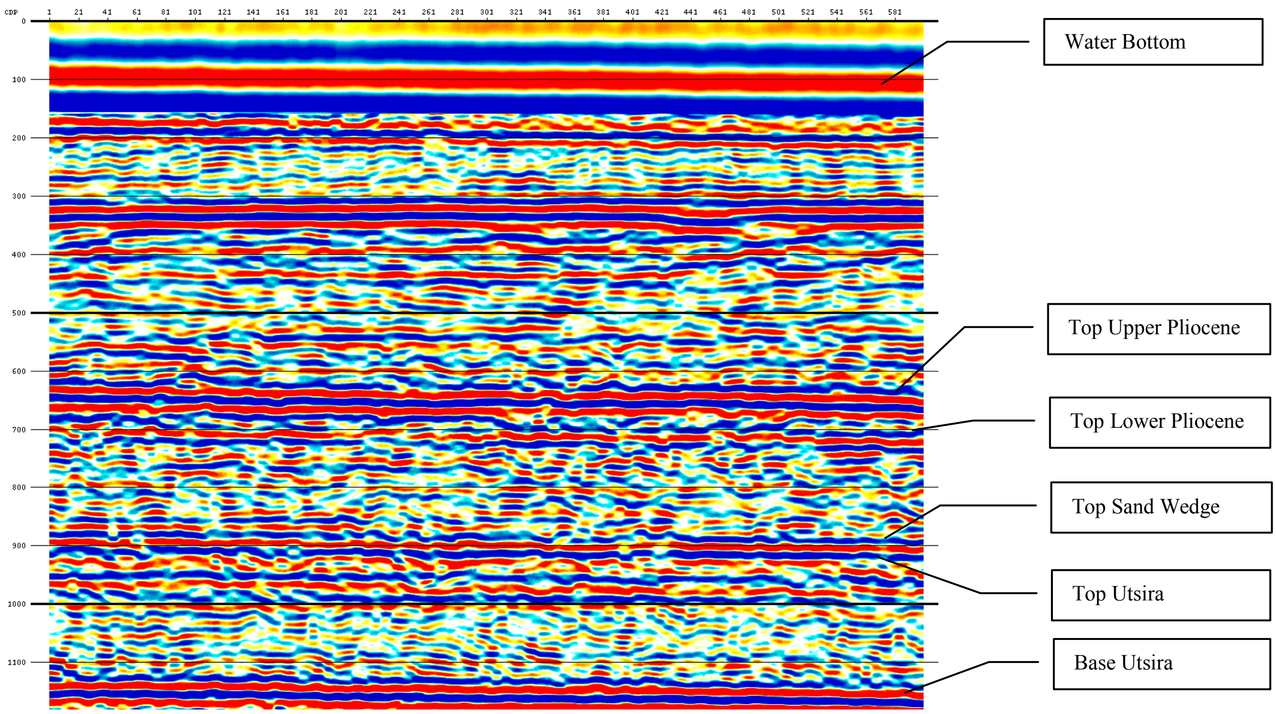

Figure 7.5 – 2-D seismic line (600 traces) recorded over the Sleipner overburden model. The horizons built within the model have been identified with the Base Utsira reflection recorded from the base of the steel water tank.

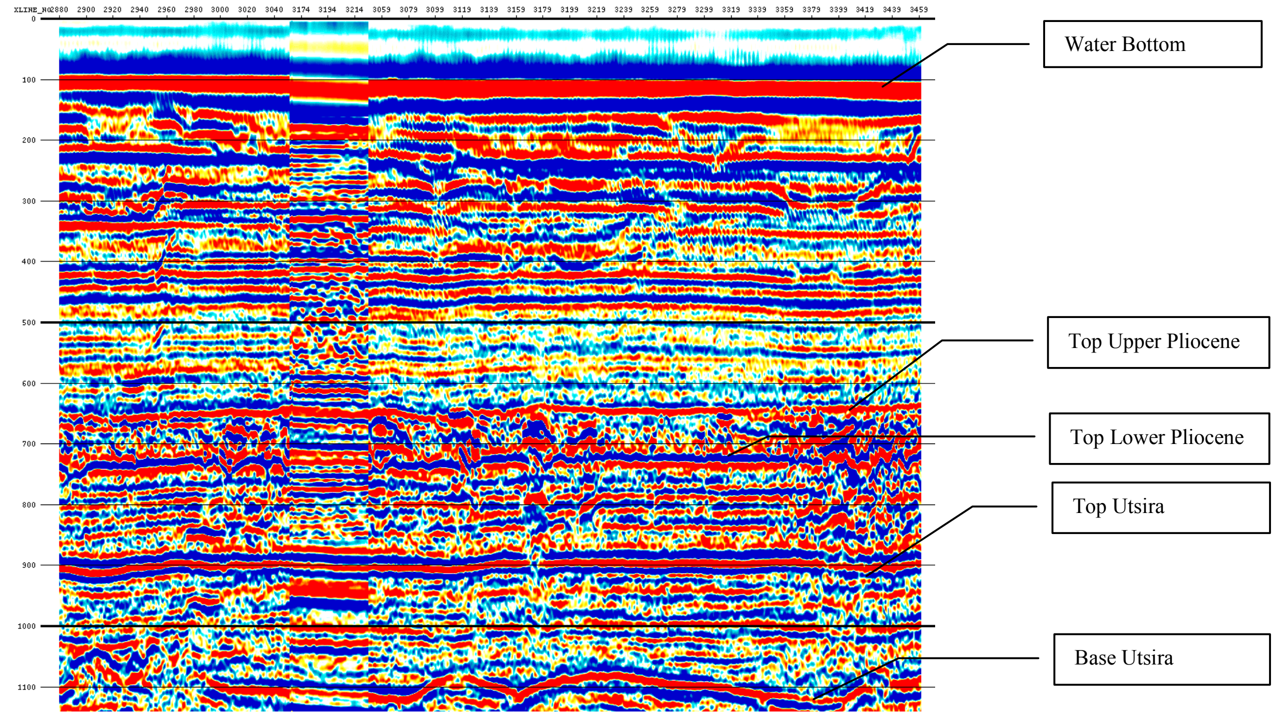

Figure 7.4 – A model stack consisting of 60 traces inserted into field Inline 3780 recorded in 1994. There are slight timing errors between some events and an almost perfect match between others. Overall, the frequency content between the two data sets appears very similar.

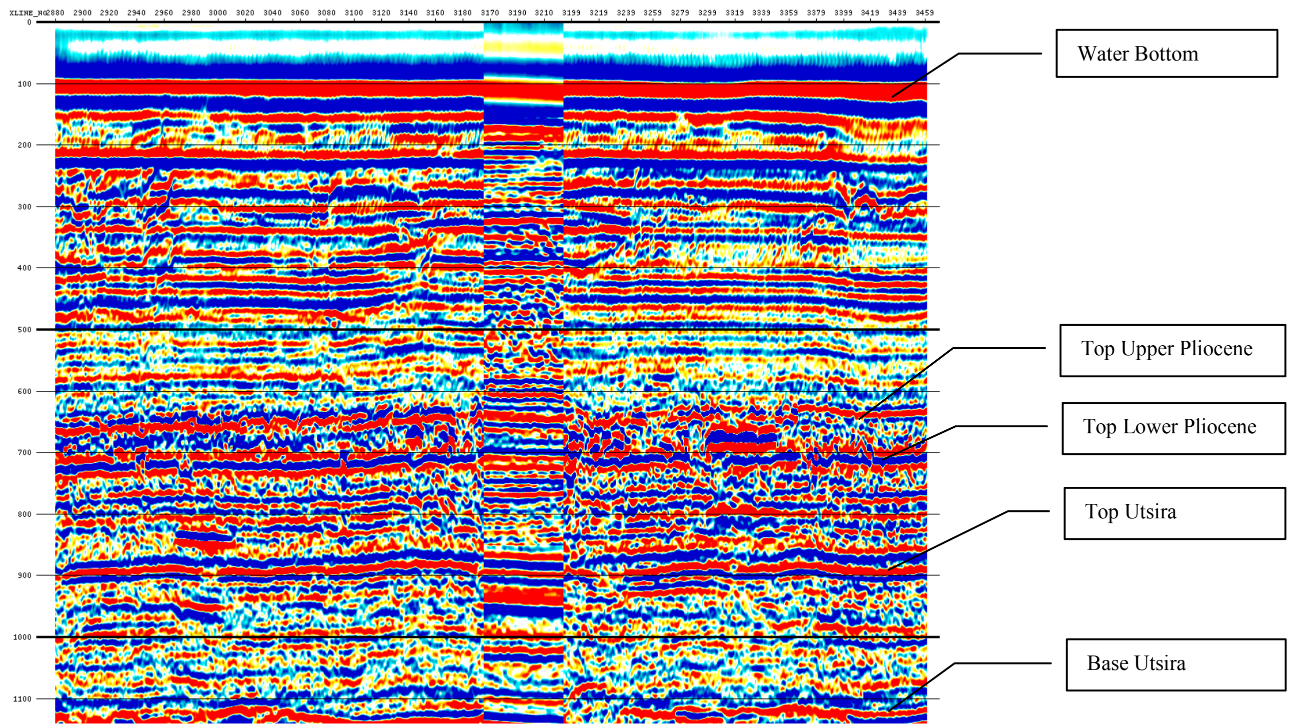

Figure 7.5 – Model stack inserted into field seismic Inline 3842 recorded in 1994. The CO_2 injection point is located to the left of the inserted model data.

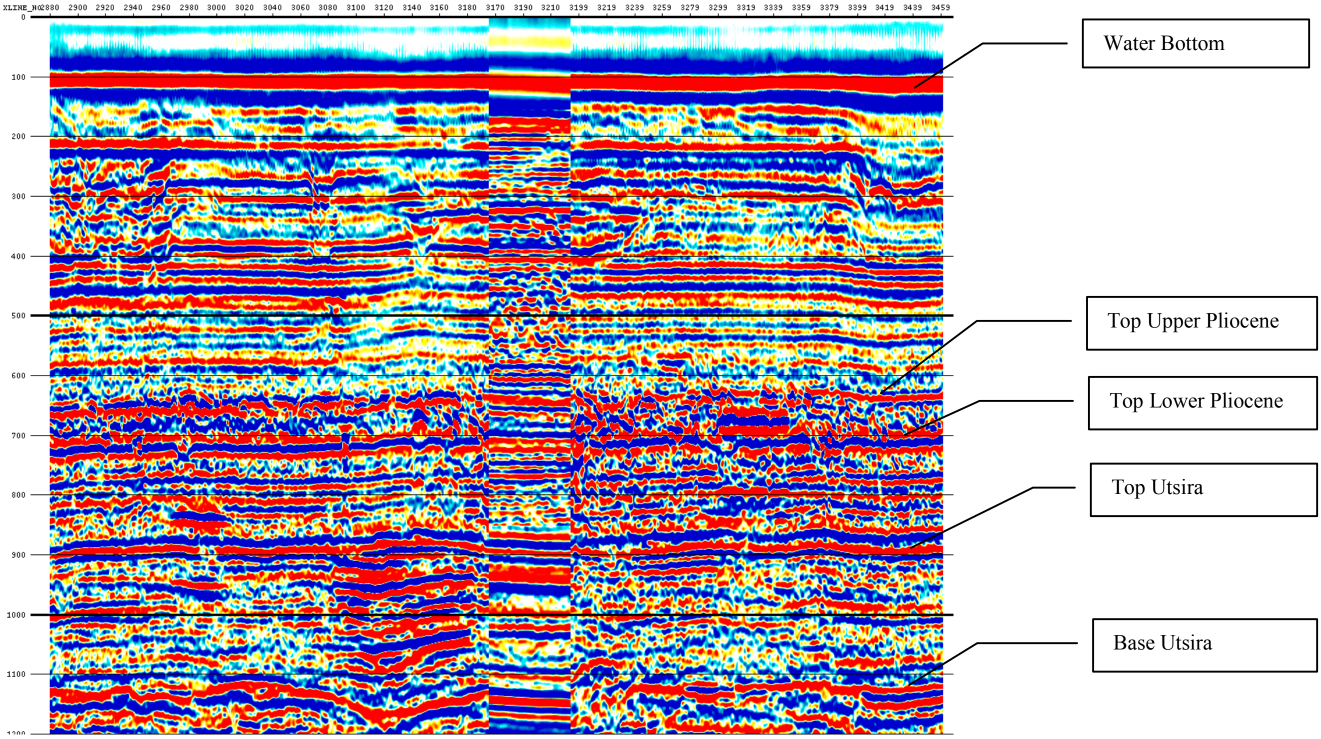

Figure 7.6 – Model stack inserted into field seismic Inline 3842 recorded in 1999 after approximately 3 million metric tonnes of CO_2 had been sequestered.

8. Numerical Modelling

Numerical modelling of the pre-stack and post-stack seismic response of the Sleipner overburden model was calculated using the GEOVIEW software. A 55 Hz zero-phase Ricker wavelet was used and the depth, density and P-wave velocity values of the numerical model were the true field values listed in Table 5.1. A common midpoint gather was calculated consisting of 120 traces with a near offset of 250 metres and a station interval of 25 metres. A CMP stack was also calculated consisting of 60 traces. Figure 8.1 illustrates the muted physical model CMP gather alongside the numerical gather. The timing match of horizons and moveout between the physical model and the numerical data appears satisfactory. Each layer within the numerical model was defined as non-attenuating and thus the reflection strength appears homogeneous throughout the numerical traces. The final numerical stack was then inserted into the field data alongside the physical model data (Fig. 8.2). The post-stack data match between all three data sets appears to be satisfactory although the physical model and field data appear to have slightly lower frequency content than the numerical data.

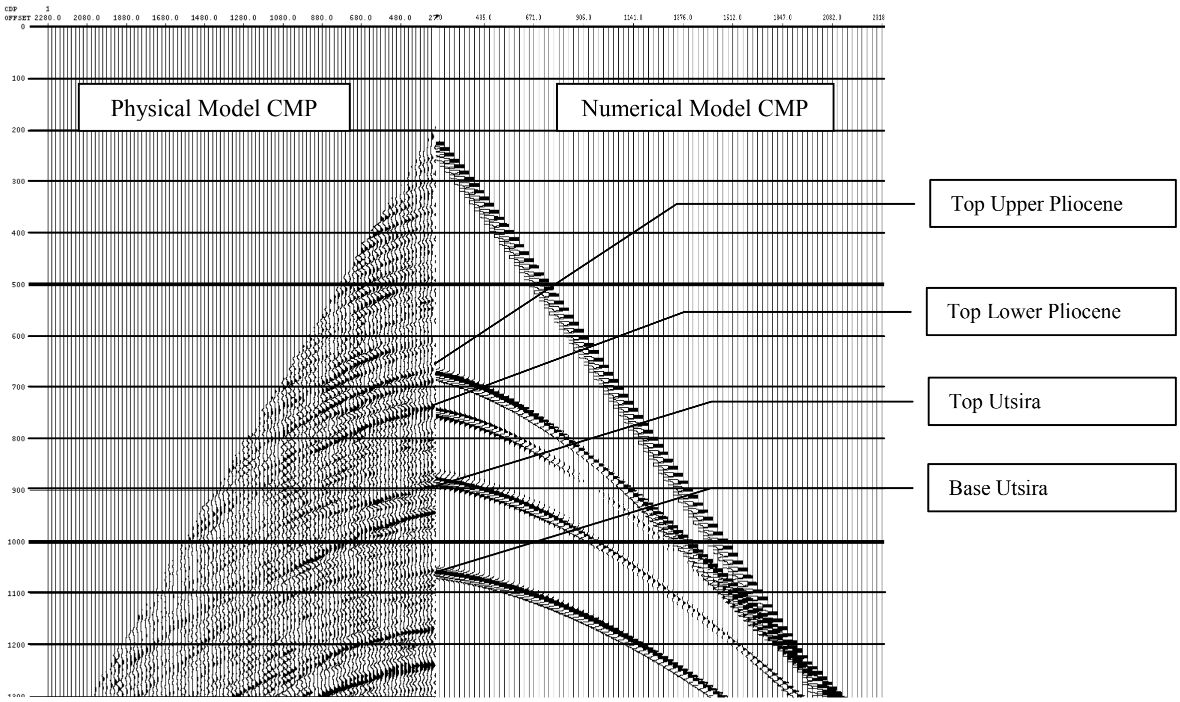

Figure 8.1 – A typical physical model CMP gather inserted alongside the numerical gather. The timing match of horizons and moveout between the physical model and the numerical data appears satisfactory.

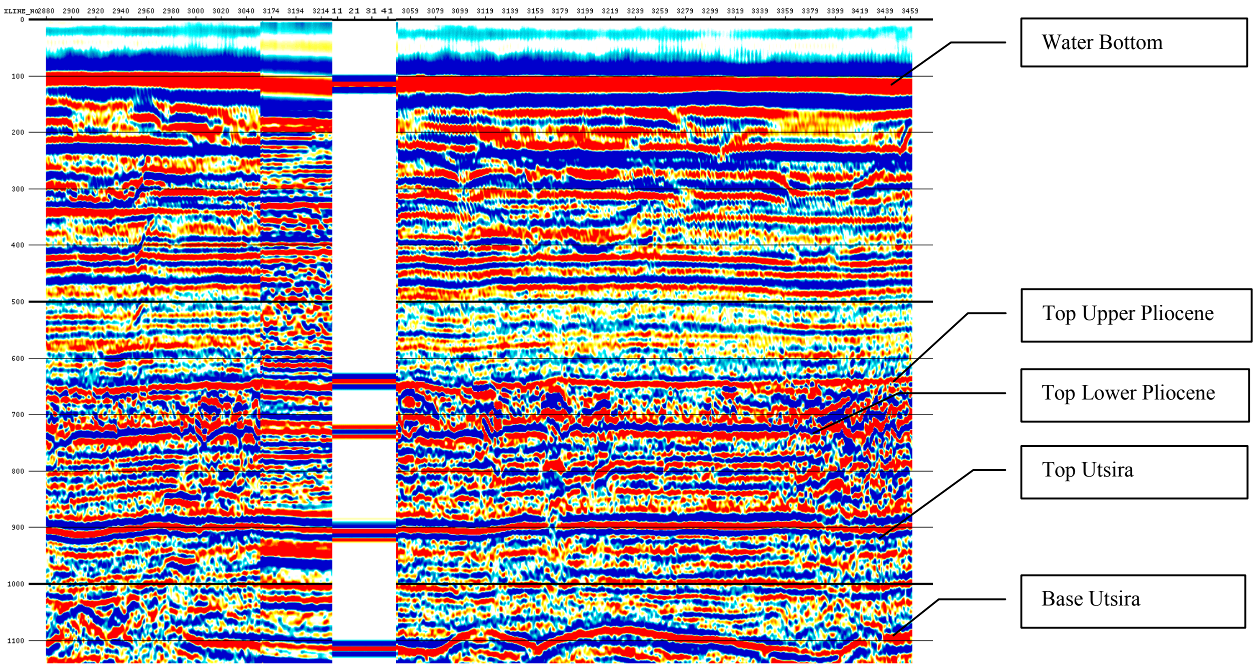

Figure 8.2 – Both physical and numerical model stacks inserted into field Inline 3780 recorded in 1994. The frequency content of the physical model and field data appear slightly lower than the numerical data, which is consistent with the higher frequency wavelet used in the numerical calculation.

9. Conclusions

A physical model representative of the sedimentary sequence overlying the Utsira Formation at Sleipner West has been constructed at a scale of 1:5000. The model was constructed from a two component plastic compound using varying amounts of added limestone powder to match the interval P-wave velocities of the sedimentary sequence. Density values were matched to approximately 70% of the true field values. Scaled seismic data was acquired over the model and compared with both pre-stack and post-stack field data from the 1994 seismic survey. A satisfactory match between the physical model and field data was achieved in both pre-stack and post-stack data sets without the use of aggressive matching filters commonly used when comparing time-lapse data sets. A comparison between physical modelling and numerical modelling illustrated the physical model to provide a superior data match.

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